

Novel Applications of Soft X-ray Scattering for Condensed Matter Studies

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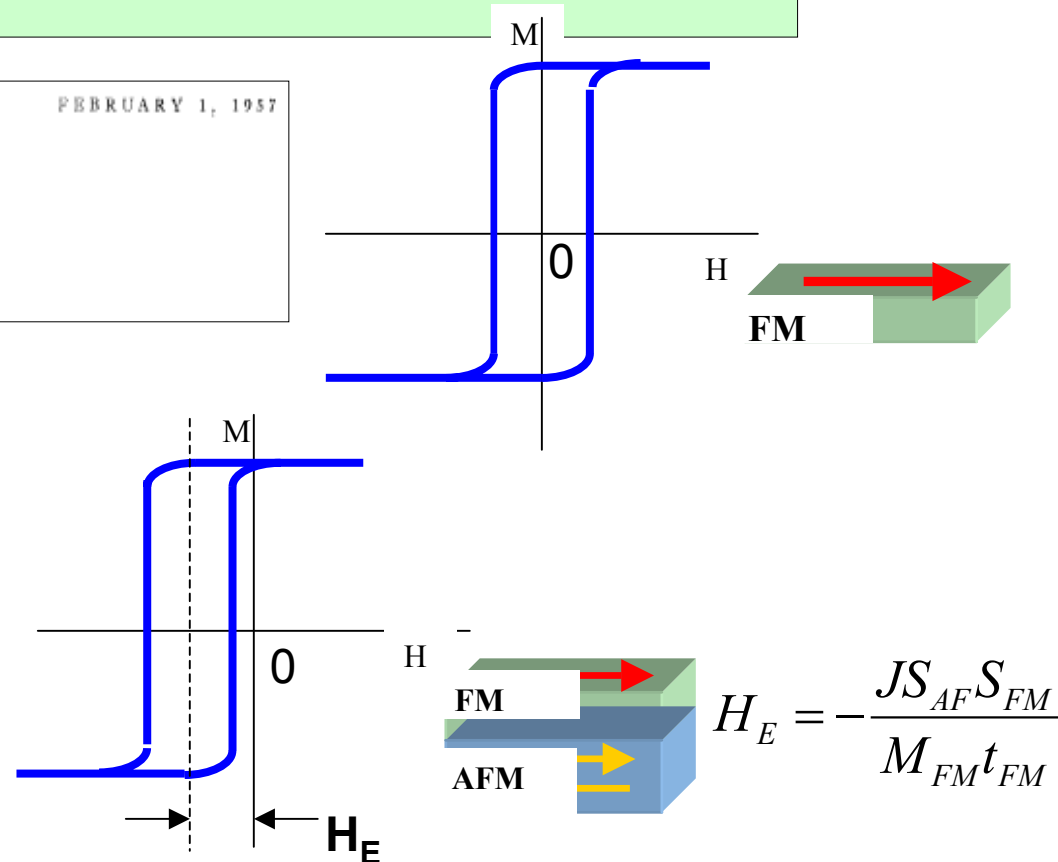
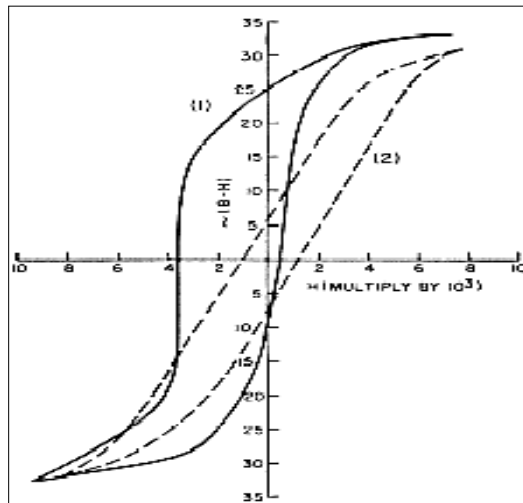
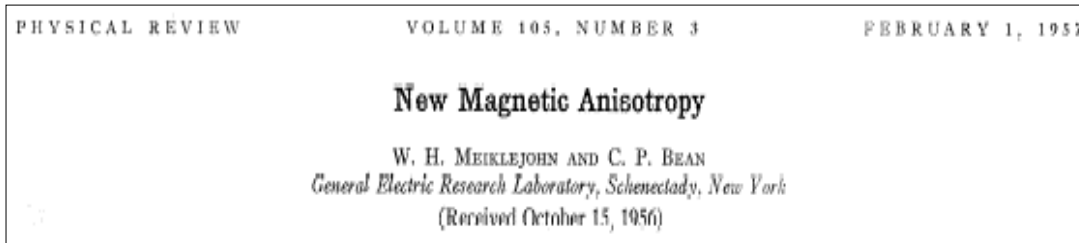
Scattering Techniques with Soft X-Rays

- Resonant Bragg scattering and satellite peaks: long and short range order and modulations (orbital, magnetic).
- Resonant diffuse Scattering: local distortions of lattice, magnetic and electronic structure.
- Resonant magnetic reflectivity and off-specular scattering: Magnetic structure of interfaces and thin films.
- Resonant Small Angle Scattering; Spatial distribution of bonding states.
- Resonant Inelastic Scattering: Electronic Excitations.
- Coherent Soft X-Ray Scattering: Imaging; Dynamics

Applications

- Magnetic Thin Films: Exchange bias problem; Spin Injection in semiconductors; GMR.
- Complex Oxides: Hole ordering; Orbital Ordering; Electronic modulations in High-Tc superconductors.
- Strongly correlated Systems: Kondo Lattices; Quantum Critical Phenomena.
- Soft Condensed Matter: polymer structure and surface dynamics of liquids and biomembranes.

The Exchange Bias Phenomenon



- W.H. Meiklejohn, C.P. Bean, *Phys. Rev.* **105**, 904 (1957).
 J. Nogués, Ivan K. Schuller, *JMMM* **192**, 203 (1999).
 A.E. Berkowitz, K. Takano, *JMMM* **200**, 552 (1999).

➤ **EB vanishes above T_N ;**
Must be related to the AF

The formula does not represent reality !!

$$H_E = - \frac{JS_{AF} S_{FM}}{M_{FM} t_{FM}}$$

Gives bias values 2-3 order higher

Does not explain why exchange bias is observed for compensated AF surfaces like Fe/FeF₂

➤ **Does not realistically represent the FM/AF interfacial environment**

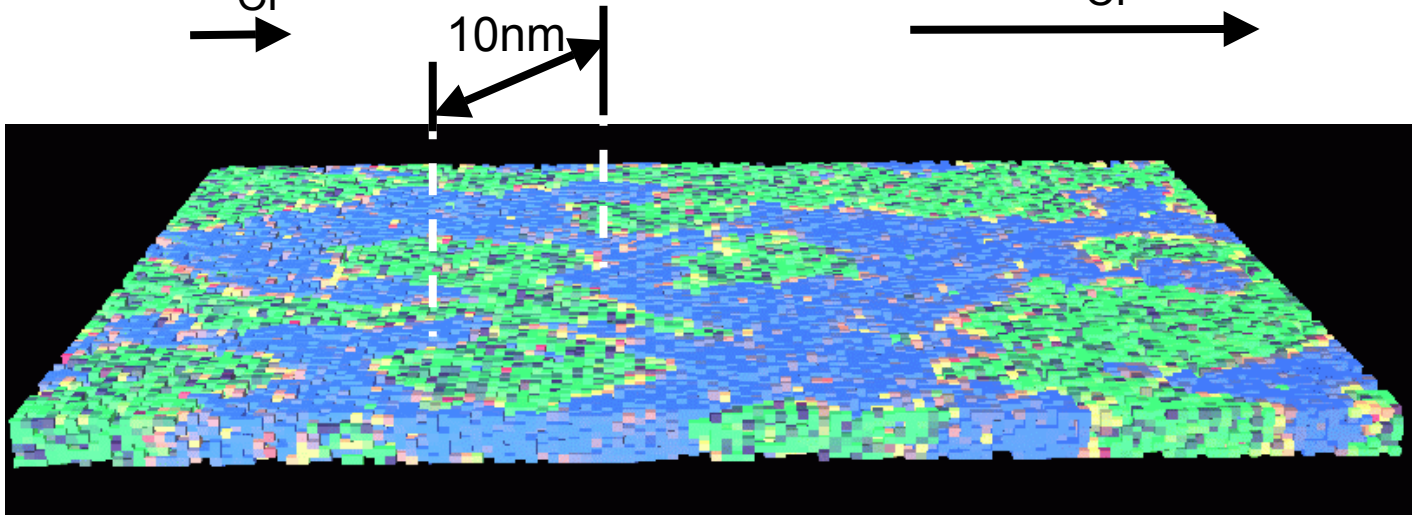
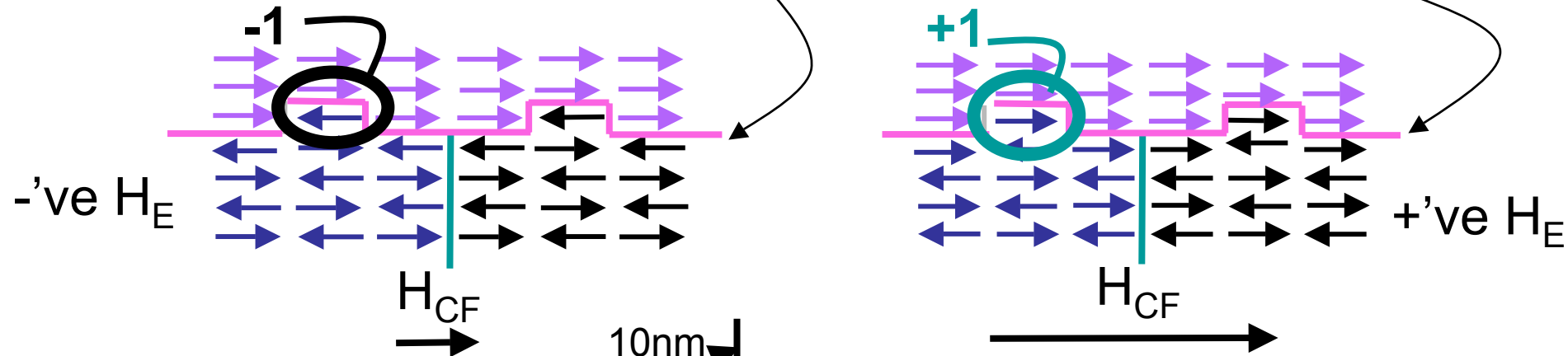
Various models proposed:

- ✓ Random Field Model (Malozemoff, *Phys. Rev. B* 35 (1987) 3679)
- ✓ Domain Wall Model (Mauri *et al*, *J. Appl. Physics* 62 (1987) 3047)

Random-field, domain state, etc., models

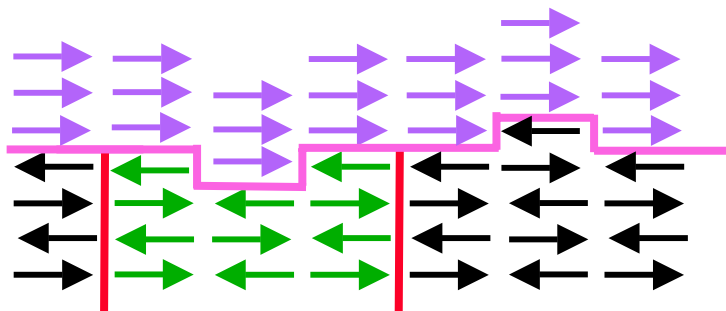
Super exchange (AF-coupling)

Frustrated super exchange (AF-coupling)



U. Nowak et. al., *J. Magn. Magn. and Mater.*, **240**, 243 (2002).
A.P. Malozemoff, *J. Appl. Phys.*, **63**, 3874 (1988).

Interfacial Spin Structure is a key to understand EB



- ✓ Interface properties could be very different from bulk
- ✓ Roughness could be a source of AF uncompensated moments
- ✓ Compelling need to determine spin structure across F/A interface (e.g. domain structure, magnetic roughness, etc.)

➤ Need interface sensitive experimental technique

Measuring Reflectivity using resonance X-ray scattering technique

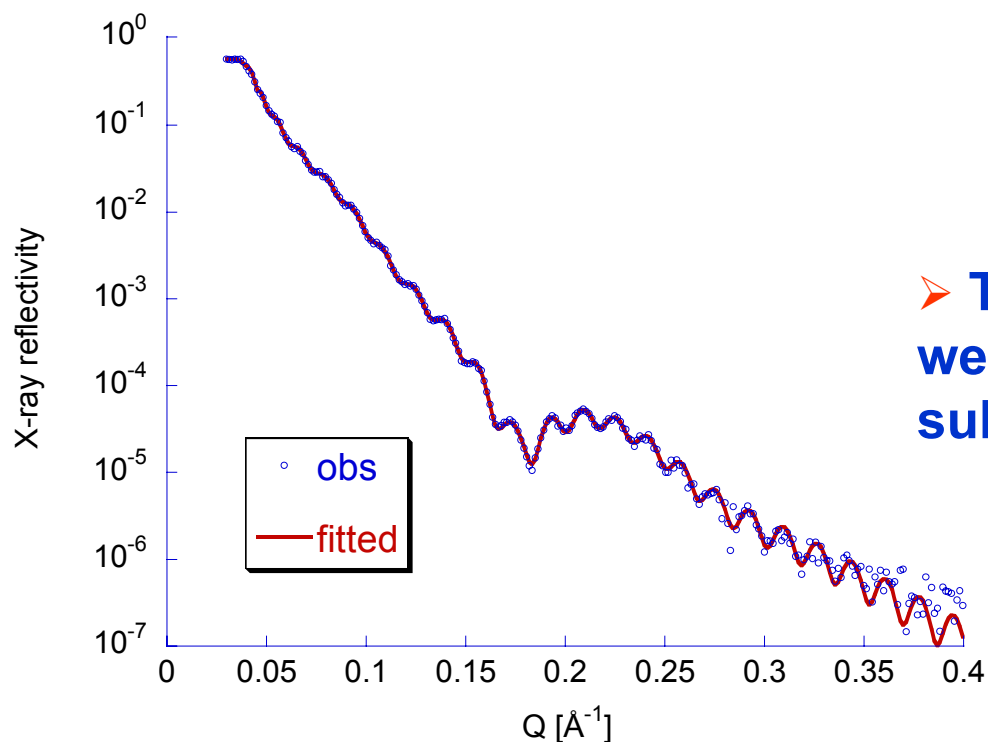
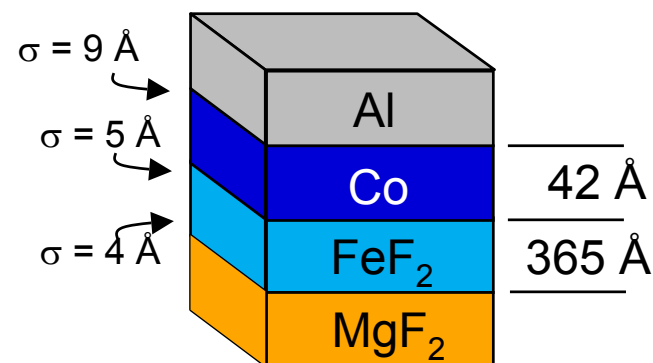
- Can *quantitatively* determine depth dependent magnetic density
- Interface sensitive
- Element Specific
- Diffuse scattering – lateral structures like domains, magnetic roughness etc.

The Sample

FeF_2 grown epitaxially on MgF_2 , Co is polycrystalline

(001) – Easy axis of FeF_2 , $T_N = 78$ K

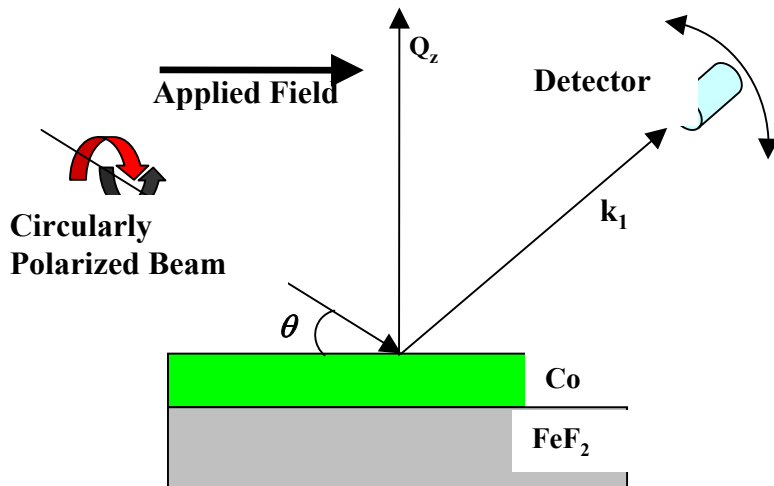
Exhibits **positive** exchange bias



➤ The thicknesses and roughness were constrained to be same for subsequent resonant reflectivity fits

The Experimental Procedure

Resonant X-ray scattering measurements performed on Beamline 4.0.2 at the ALS using Kortright endstation



Field of 1 T applied at 300 K along (001) direction

Sample field cooled through T_N to 20 K

Three types of measurements:

- (1). Hysteresis loops by switching incident beam polarization at L_3 edge of Co and Fe
- (2). Reflectivity measurements as function of Q_z by switching applied field

Info about both pinned and rotating moments

- (3). Measurement of diffuse scattering

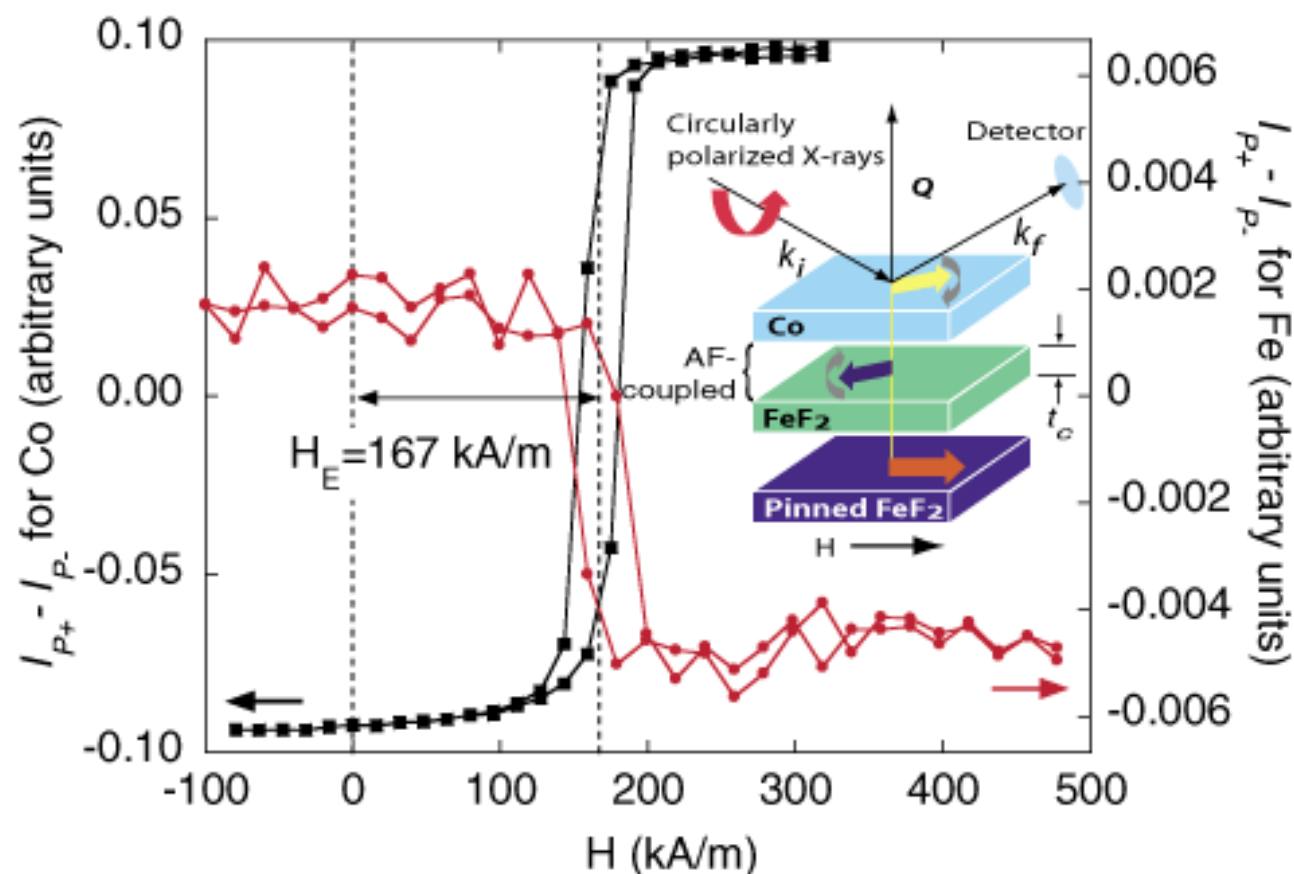


FIG. 1 (color). Hysteresis loops at $Q = 0.49$ and 0.38 nm^{-1} for Co (■) and Fe (red ●), respectively. Inset: representations of the x-ray experiment and sample.

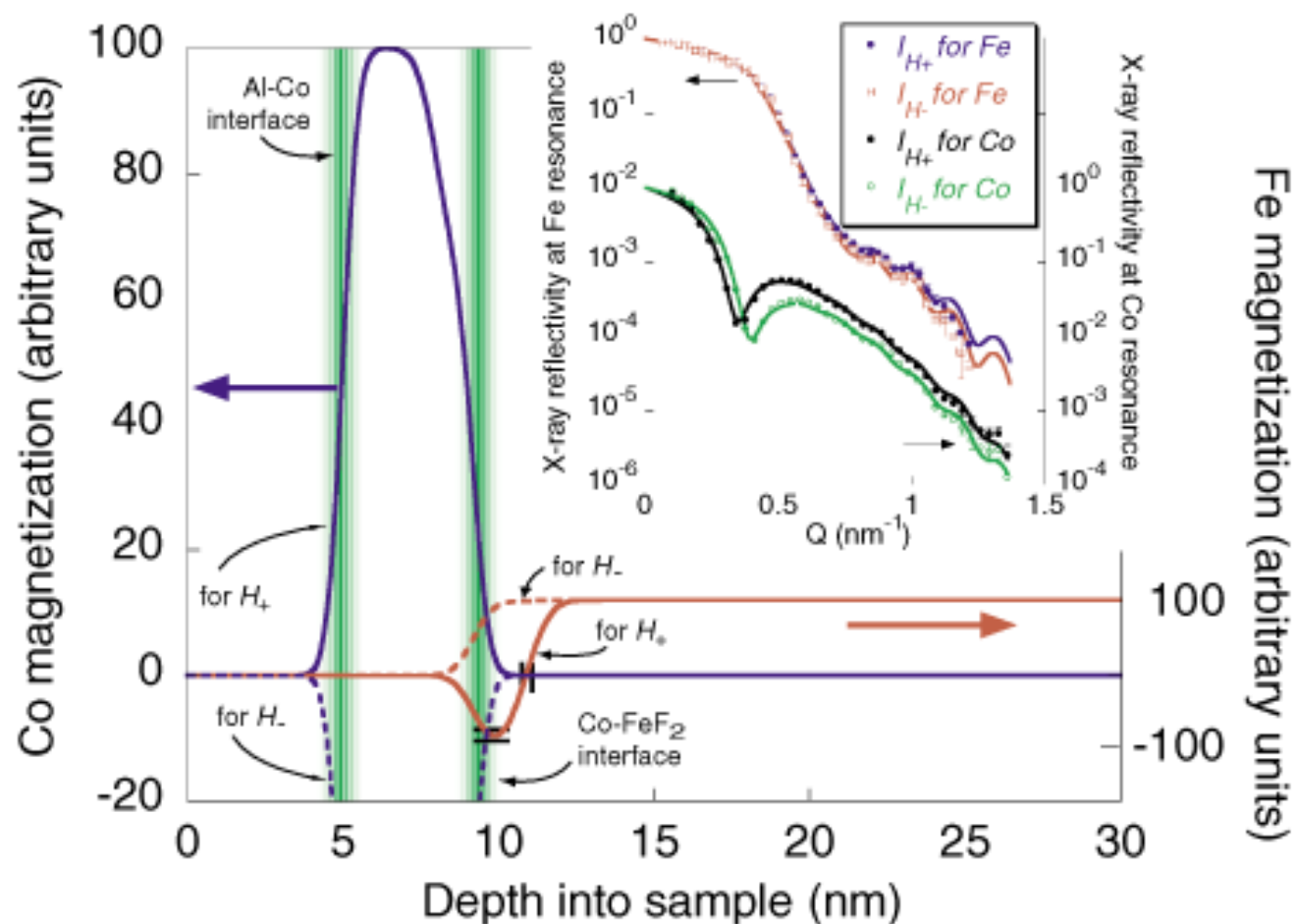
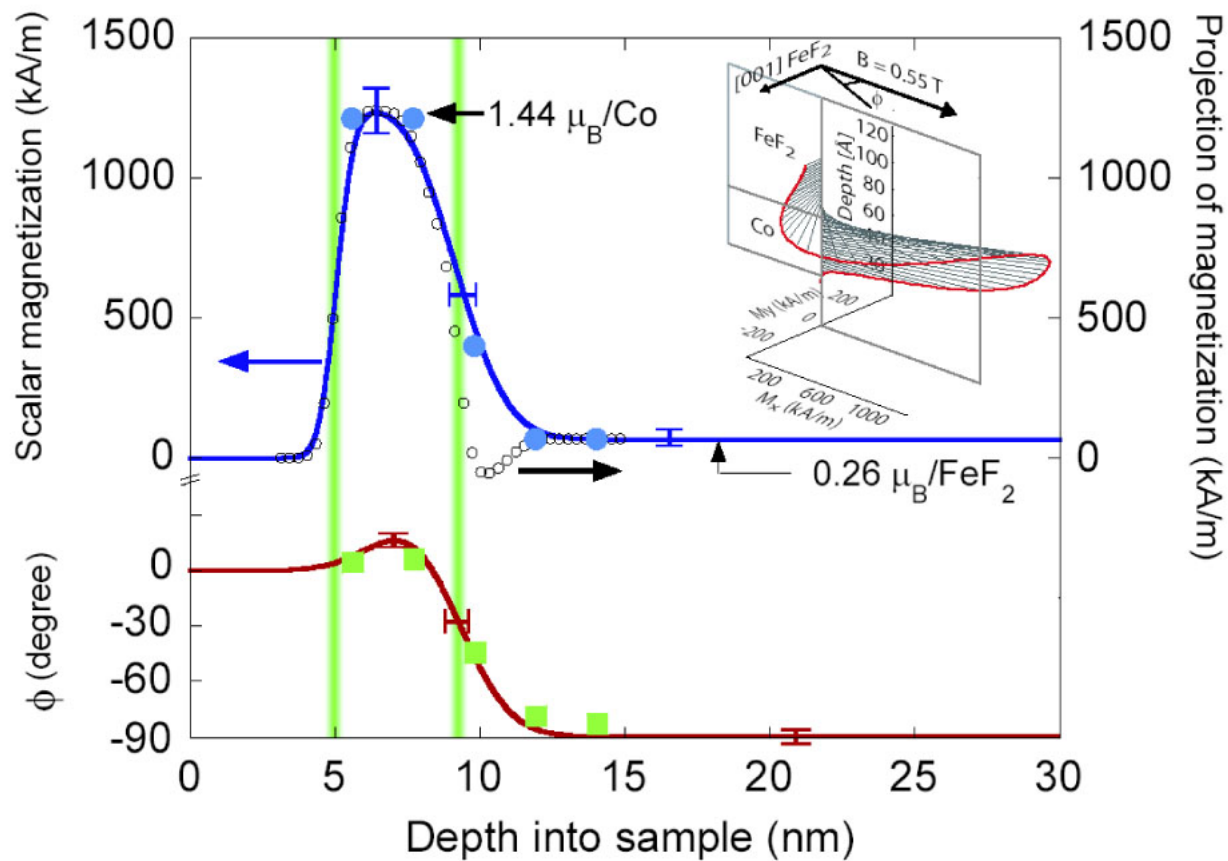
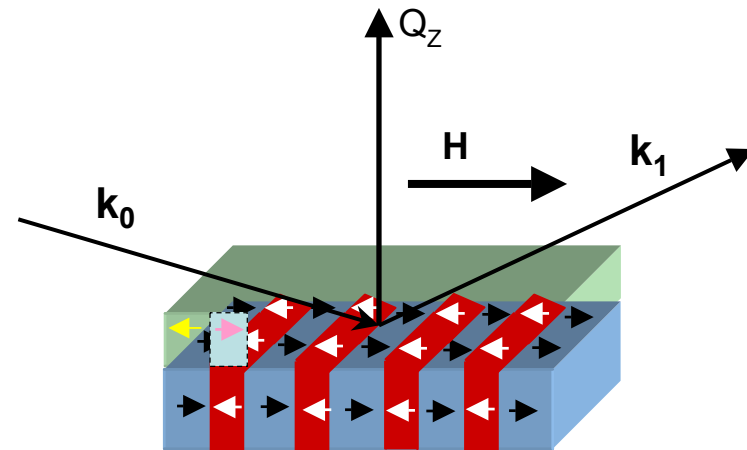
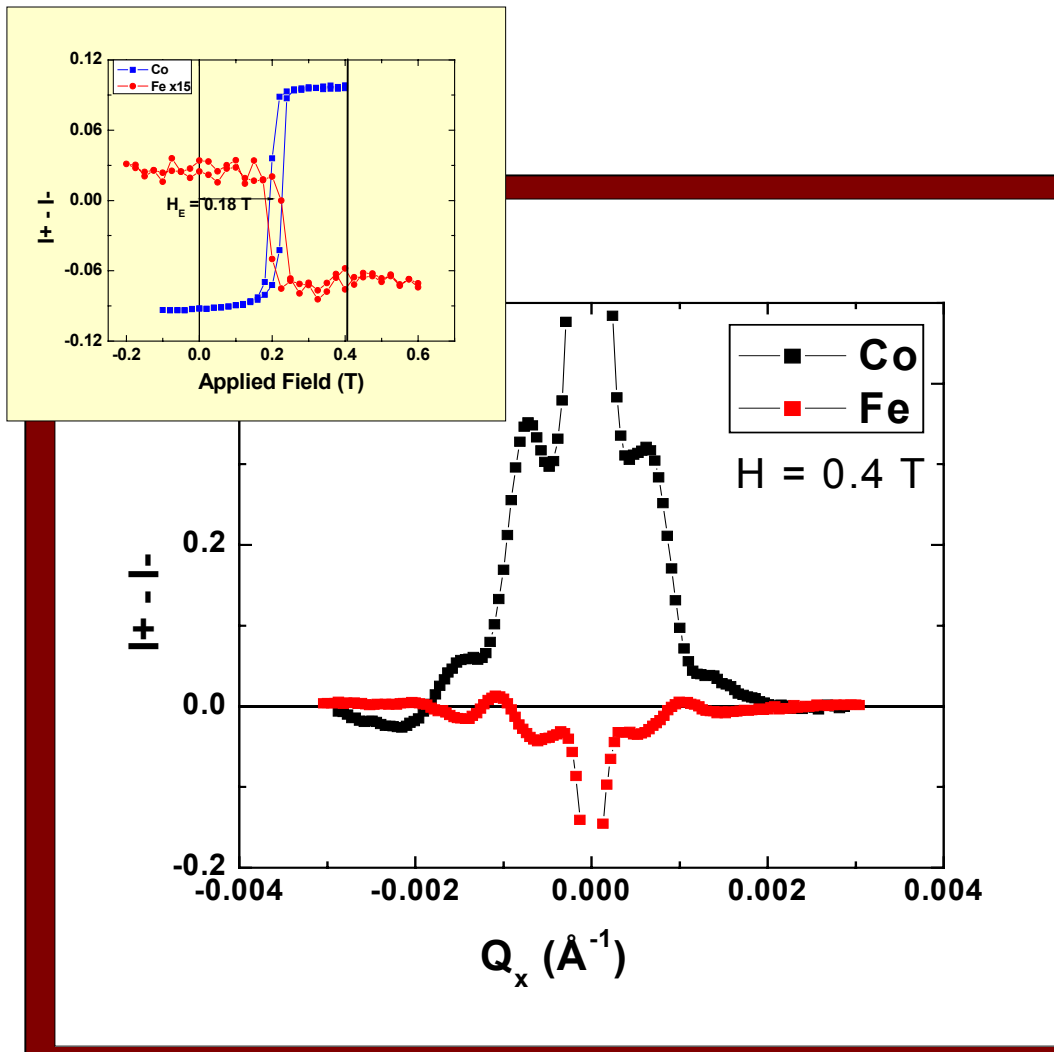


FIG. 2 (color). Spin density depth profiles for Co (blue) and Fe (red) spins obtained from the specular x-ray reflectivities (inset) at $H_{\pm} = \pm 796$ kA/m.



Diffuse Scattering at an Applied Field of 1 T



- Off specular scattering show peaks due to domains.
- Domains in the FM and AF are oppositely aligned
- Domains correlated with structural features (roughness or defect)

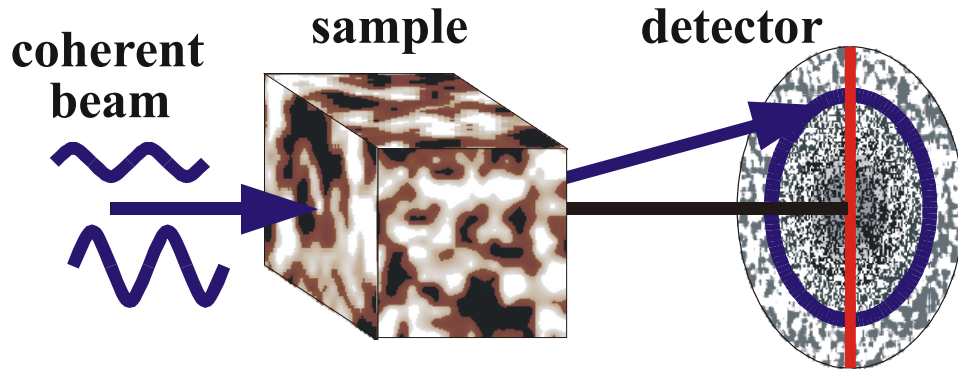
Conclusions

- Resonant X-Ray scattering combined with polarized neutron reflectivity is a powerful tool to determine in an element sensitive way the depth profile and direction of magnetism in a magnetic thin film structure
- For Co/FeF₂ system we found that
 - ✓ interface coupling is antiferromagnetic
 - ✓ existence of pinned and rotating moments for Fe
 - ✓ interface mostly contains rotating moments while the bulk contains pinned moments (from neutron scattering results)
 - ✓ exchange bias is due to exchange interaction between Fe pinned and Fe rotating moments
 - ✓ Diffuse scattering indicates formation of domains

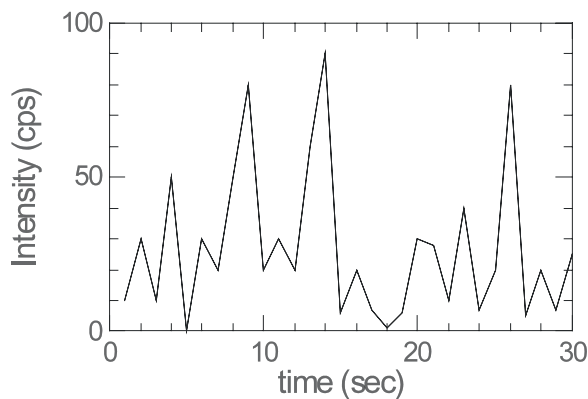
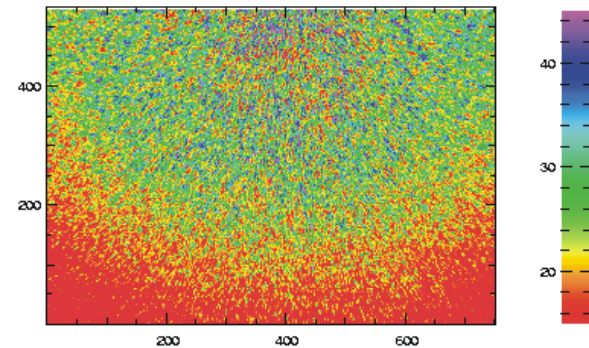
Collaborators

- Sujoy Roy, Michelle Dorn UCSD
- Ivan Schuller, O.Petracic, Zhipan Li, Igor Roshchin UCSD
- Jeff Kortright, Karine Chesnel LBL
- Mike Fitzsimmons, Sungkyun Park LANL
- DOE/BES

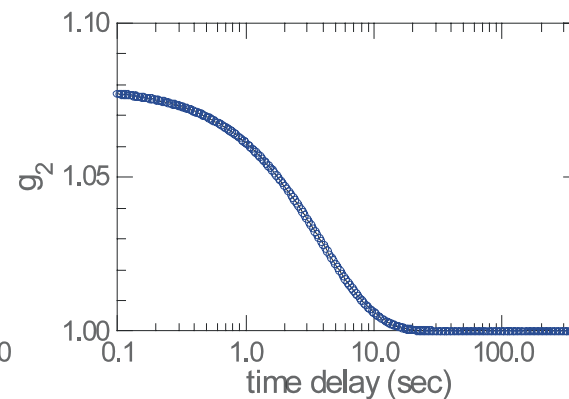
Photon Correlation Spectroscopy



X-ray speckle pattern from a static silica aerogel

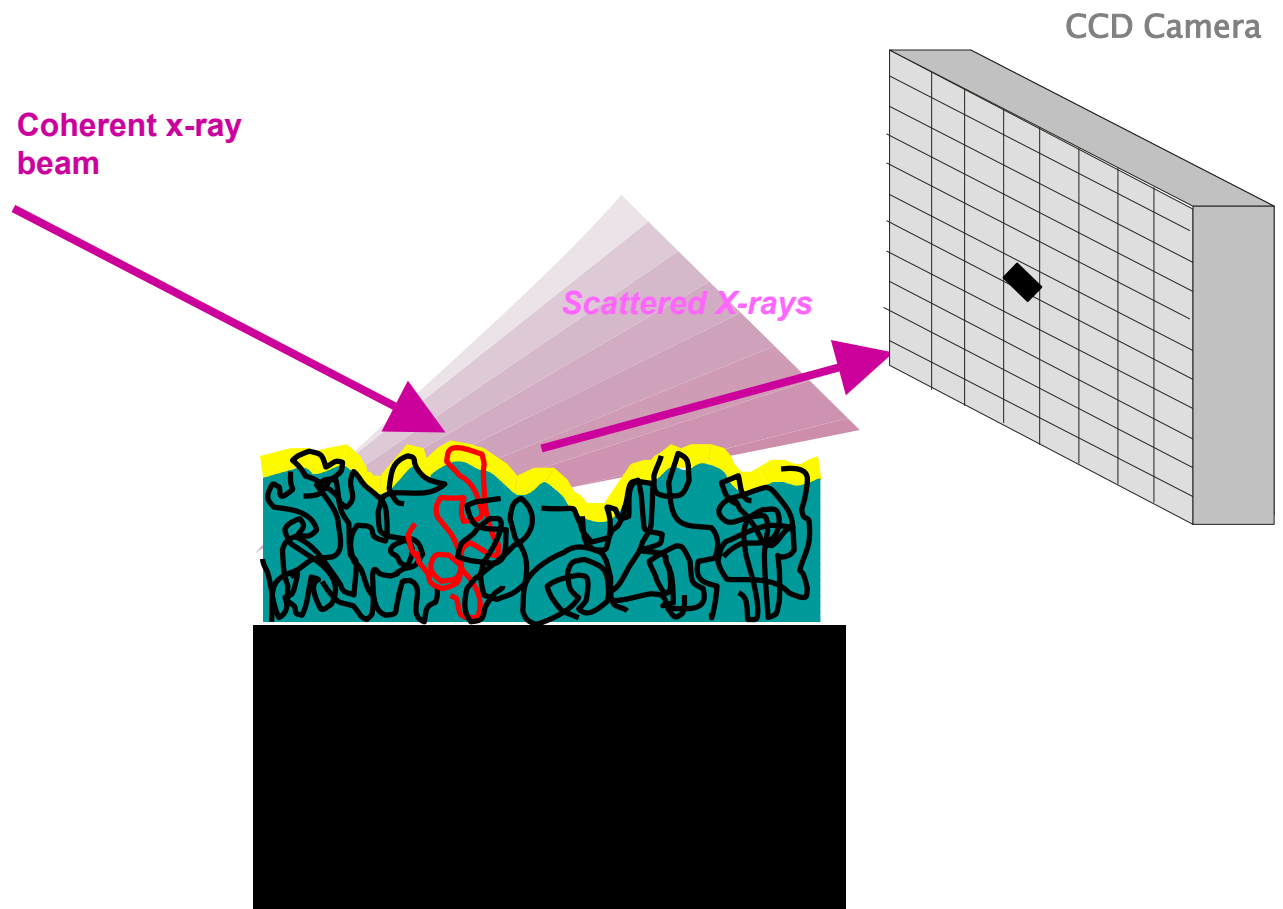


$$g_2(\mathbf{q}, t) = \frac{\langle I(\mathbf{q}, t') I(\mathbf{q}, t' + t) \rangle}{\langle I(\mathbf{q}, t') \rangle^2}$$



$$g_2(t) = 1 + \beta \exp(-2\Gamma t) \\ = 1 + \beta \exp(-2t / \tau)$$

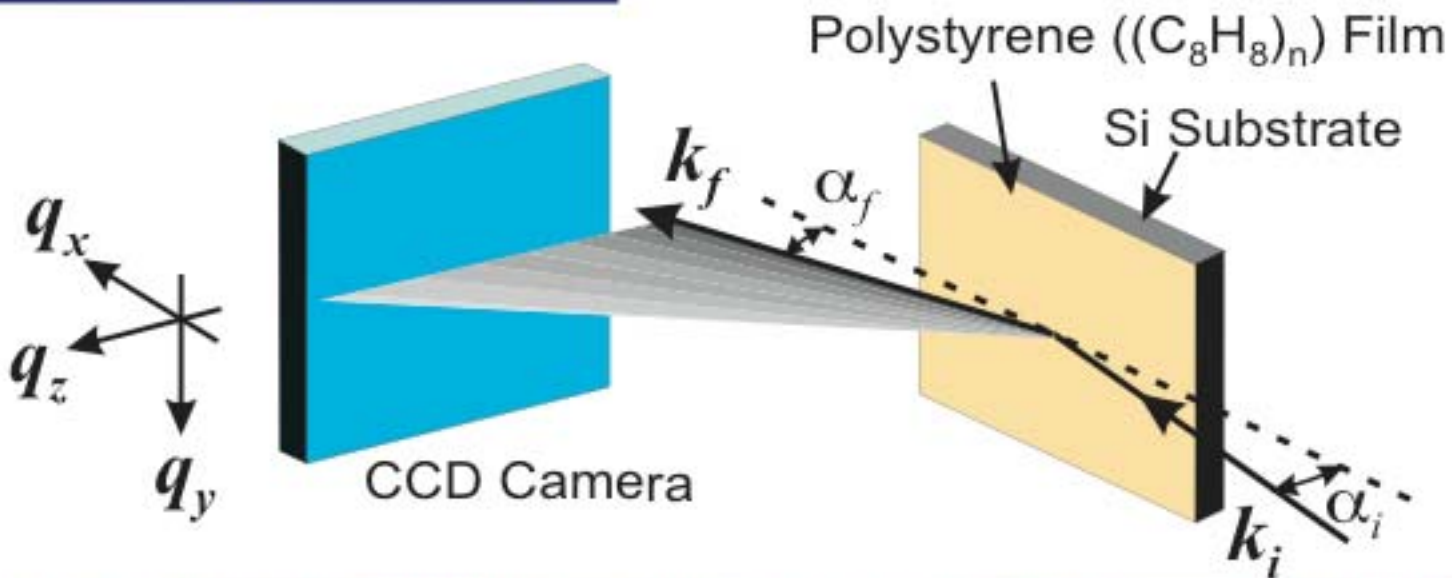
β : speckle contrast



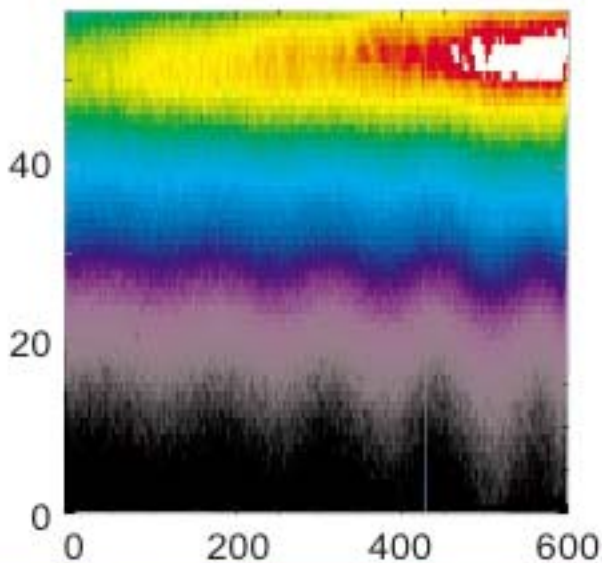
Overdamped Capillary Waves on Viscous Polymer Liquid Films

H.-J. Kim et al., Phys. Rev. Lett. 90, 068302 (2003)

Scattering Geometry

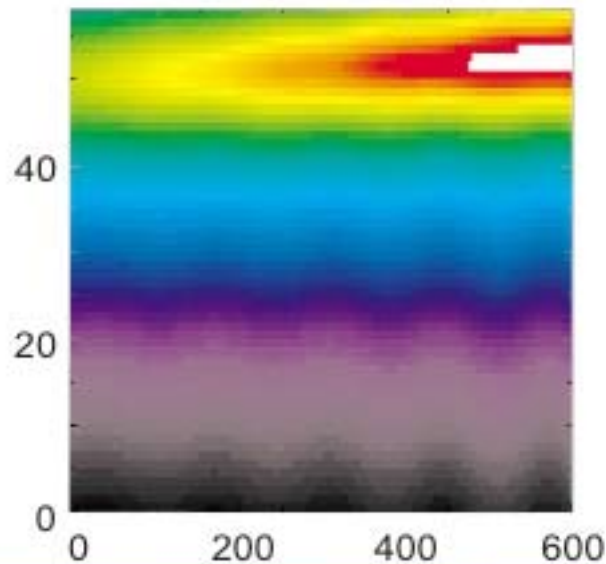


Measured Scattering



$h = 840 \text{ \AA}$
 $T = 160^\circ \text{C}$

Fit to Capillary Wave Model



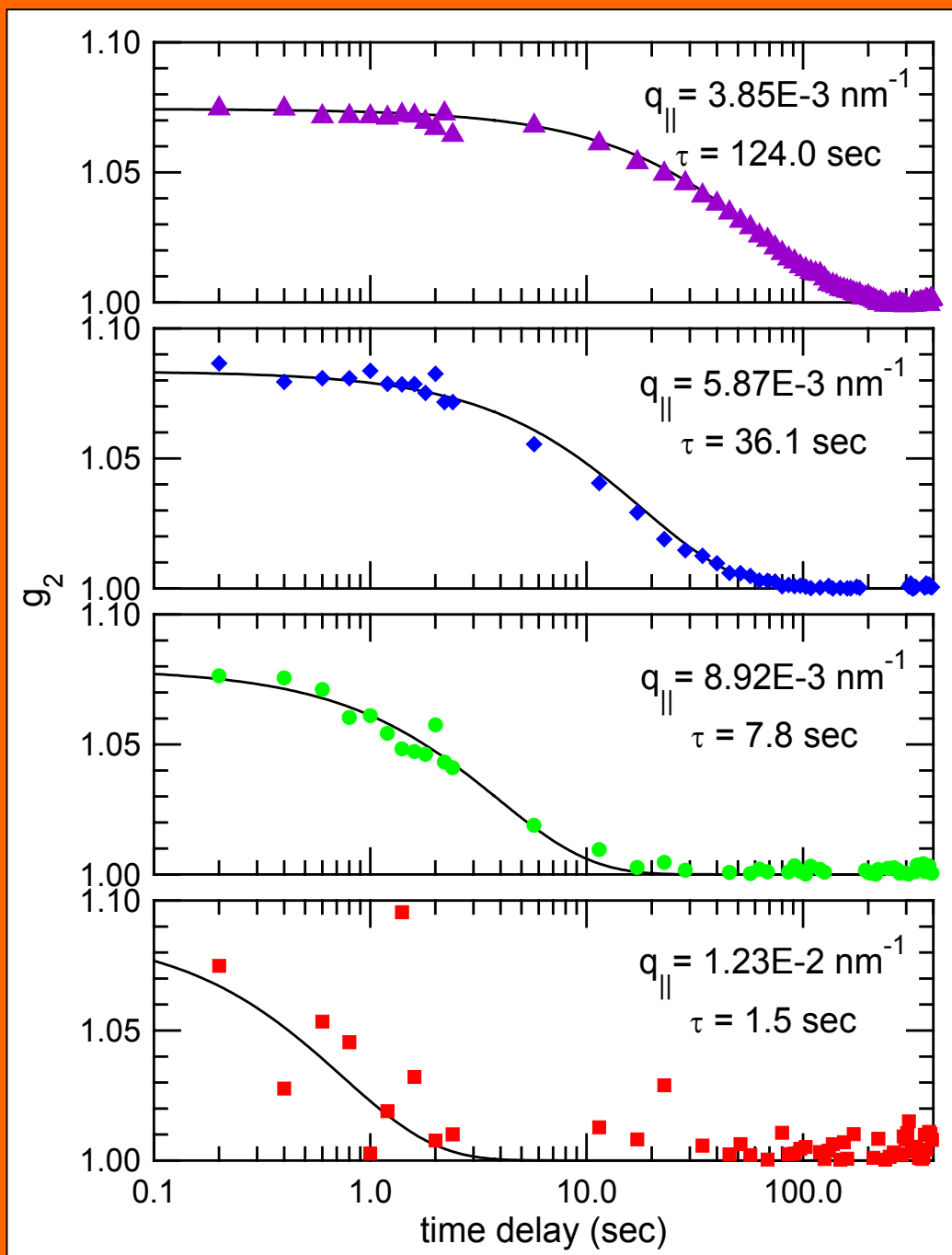
Intensity Autocorrelation

$$g_2(\mathbf{q}, t) = \frac{\langle I(\mathbf{q}, t') I(\mathbf{q}, t' + t) \rangle}{\langle I(\mathbf{q}, t') \rangle^2}$$

$$g_2(t) = 1 + \beta \exp(-2\Gamma t)$$

$$= 1 + \beta \exp(-2t / \tau)$$

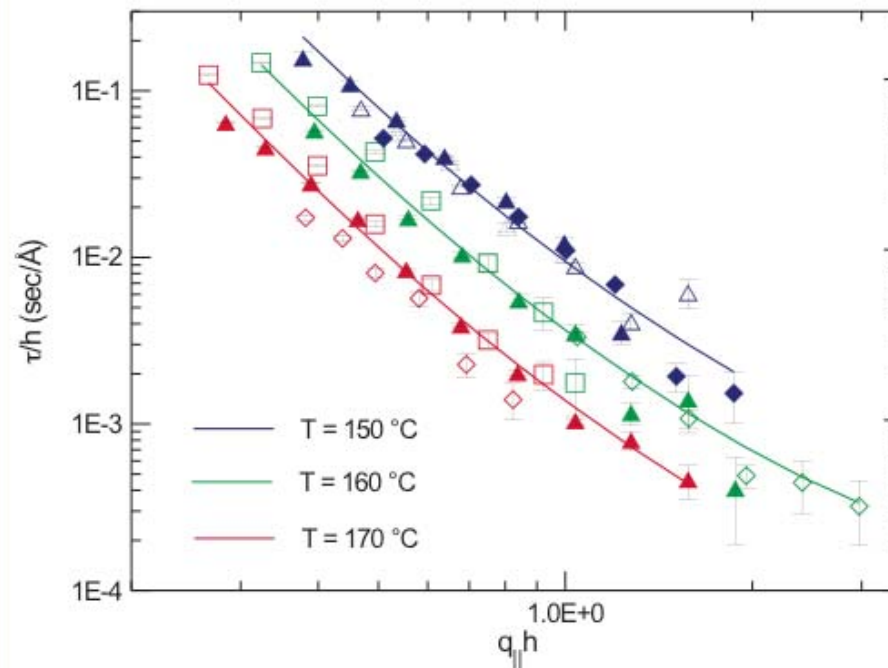
$h = 840 \text{ \AA}$, $T = 160 \text{ }^\circ\text{C}$



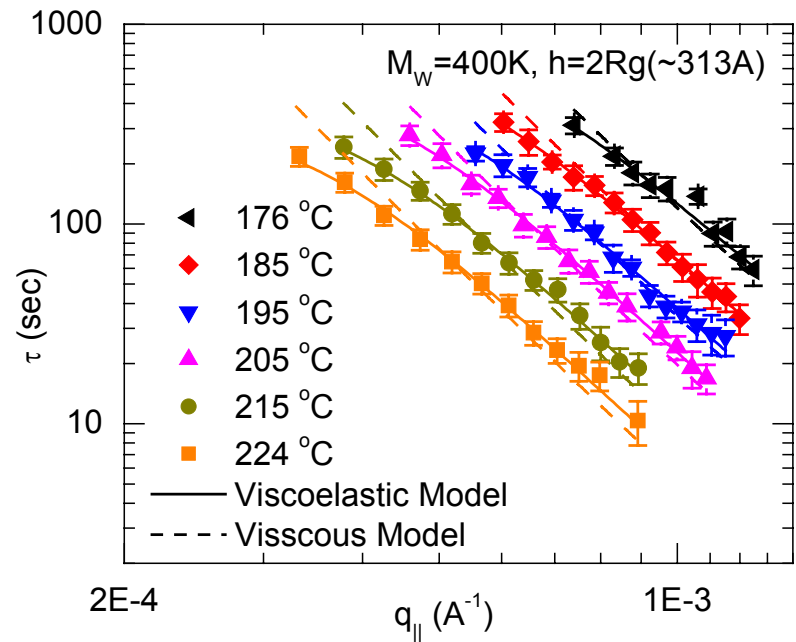
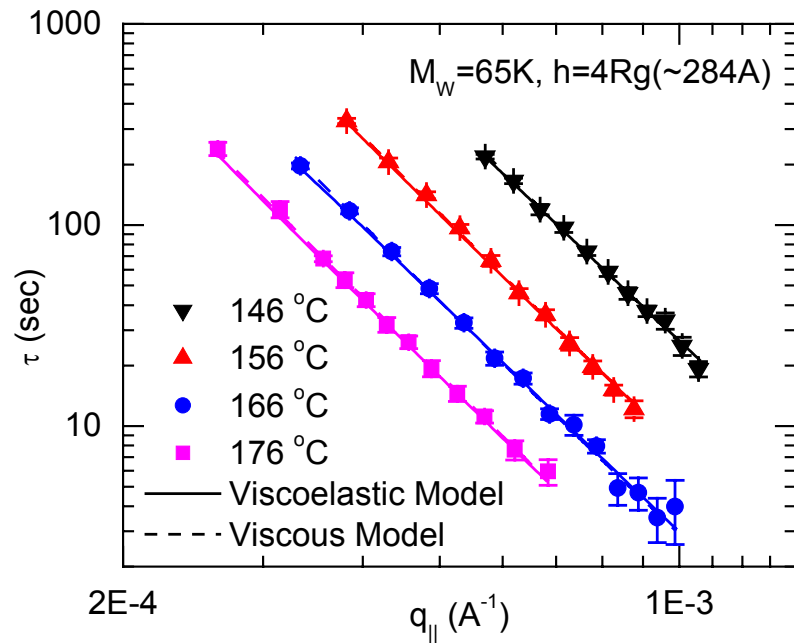
Scaling

At the values of q_{\parallel} probed here, it turns out that the second term on the right-hand side of Eq. (5) is negligible compared to the first. Similarly, it is well-justified to neglect the second term in the numerator of Eq. (1). It follows that

$$\tau \cong \frac{2\eta H}{\gamma q_{\parallel} F}$$



Tau vs. q



Tau vs. q for 65K (4Rg) and 400K (2Rg). Both films have similar thickness $\sim 300A$

$$\tau(k) = \frac{\tau_0(k)}{1 + \tau_0(k)(\mu / \eta)} = \frac{\tau_0(k)}{1 + \tau_0(k) / \tau_m}$$

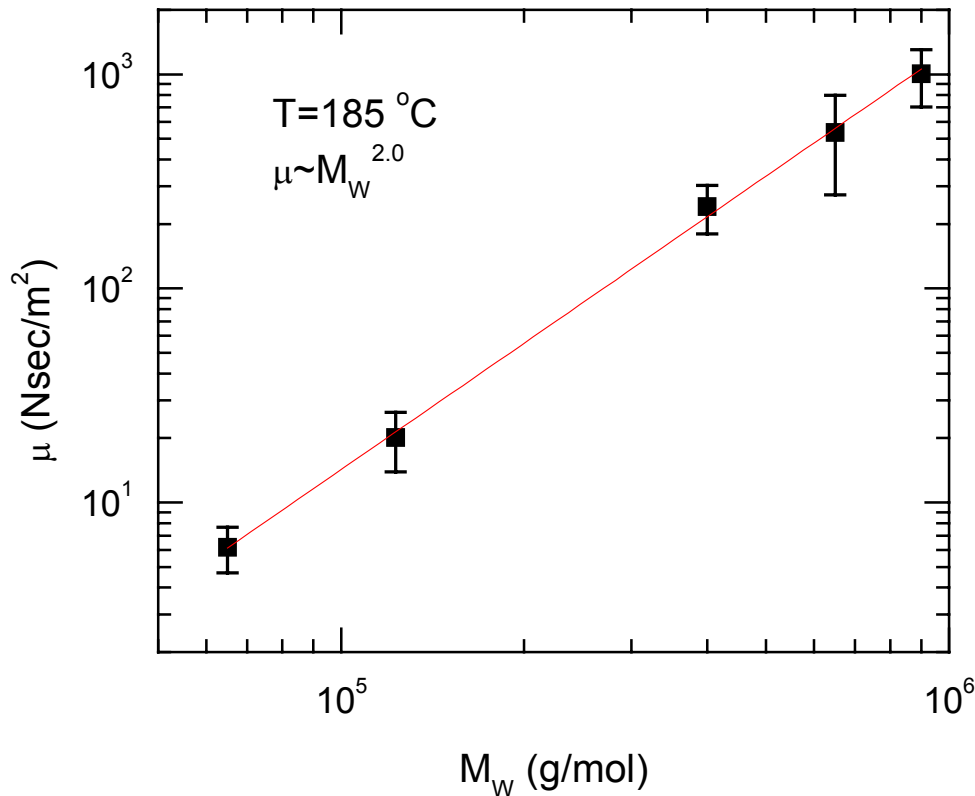
$$\tau_m \equiv \frac{\eta}{\mu} \quad \text{Tau_m is defined to be Maxwell relaxation time for a viscoelastic liuqid.}$$

$$F = \sinh(kh) \cosh(kh) - (kh)$$

$$H = \cosh^2(kh) + (kh)^2$$

$$\tau_0(k) = \frac{2\eta H}{\gamma k F}$$

Mu vs. Mw @ 185C



Equation:
 $y = a \cdot x^b$

$\chi^2/\text{DoF} = 0.08465$

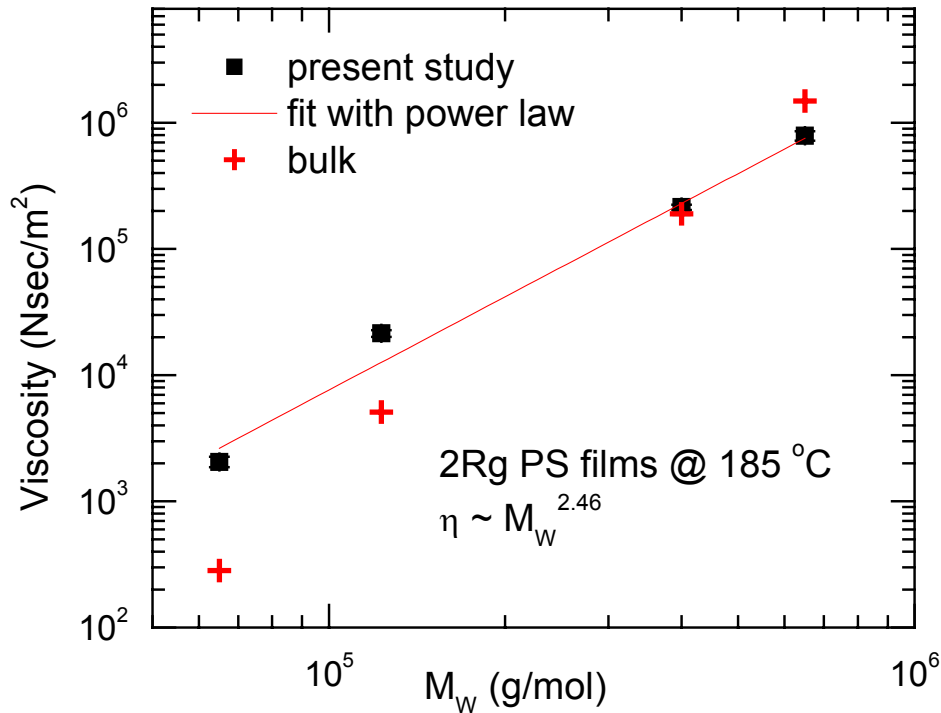
$R^2 = 0.99258$

$a = 2.2281\text{E-}9 \pm 3.4548\text{E-}9$

$b = 1.96117 \pm 0.12524$

Note: Although shear modulus μ shows a scaling with M_w , but the fit is not good the error of the coefficient 'a' is very large.

Viscosity of 2Rg films @ 185C



Equation:
 $y = a \cdot x^b$

Chi²/DoF = 28.04383

R² = 0.92408

a = 3.9852E-9 ± 2.0437E-9

b = 2.45621 ± 0.04108

Collaborators

- Zhang Jiang, (UCSD)
- Hyunjung Kim, Y. Lee, H.Lee (Sogang U.)
- Miriam Rafailovich, J. Sokolov, Kwanwoo Shin, Y.S. Seo, Chunhua Li (SUNY StonyBrook)
- Larry Lurio, Xuesong Jiao (NIU/APS)